CORE
Metadata, citation and similar papers at core.ac.uk
Provided by Texas A&M Repository

PRECISE DISPLACEMENT SENSOR AND STM COARSE APPROACH CHARACTERISTICS

An Undergraduate Research Scholars Thesis

by

KYLE TING

Submitted to the Undergraduate Research Scholars program
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Research Advisor: Dr. Glenn Agnolet

May 2016

Major: Physics and Astronomy

TABLE OF CONTENTS

ABSTRACT

Precise Displacement Sensor and STM Coarse Approach Characteristics

Kyle Ting
Department of Physics and Astronomy
Texas A&M University

Research Advisor: Dr. Glenn Agnolet
Department of Physics and Astronomy

The Coarse Approach mechanism of a STM is critical to the operation of a STM. Therefore a clear understanding of the characteristics of its motion is essential. To do so, we need an accurate sensor that is cost efficient and fits within the existing apparatus. To complement an existing fiber-optic interferometer, we decided to design and fabricate a single ended capacitive displacement sensor that will eliminate some of the drawbacks of the optical interferometer such as direction ambiguity and loss of sensitivity of the step size. The goal is to use the tools produced in this experiment and utilize them in future experiments that focus on data taking inside a cryostat.

ACKNOWLEDGMENTS

The entire experiment was aided by Dr. Glenn Agnolet and his graduate student Minjie Lu. This includes the fabrication and machining the precise capacitive displacement sensor and some of the data taking. The experiments could not have proceeded efficiently without the support provided by them.

NOMENCLATURE

STM	Scanning Tunneling Microscope
F	Farad
m	Meter
C	Capacitance
V	Volt
Hz	Hertz
p-p	Peak to peak

CHAPTER I

INTRODUCTION

The scanning tunneling microscope (STM) is an instrument that can map the surface profile of metallic surfaces with atomic resolution. It typically consists of a scanning tip, piezoelectric motion controller and a vibration isolation system [1]. The tip is first biased with a voltage relative to the sample. When the tip is then brought very close to the sample surface, usually less than 1 nm away, a tunneling current between the tip and sample is observed. The value of the current depends exponentially on the distance between the tip and the sample. Consequently, by recording the current changes as the STM is moved across the surface, a topographical image can be mapped [2].

The main goal of this project is to determine whether a capacitance displacement sensor can be used to study the motions of the piezo-actuators that move the STM. The STM in the lab of Professor Agnolet is similar to the Pan-type motor described in the Precision Engineering Journal [3] where the STM head is moved by shear-mode piezoelectric actuators. These piezoelectric stacks move in response to the applied high voltage signals. These movements, typically around a nanometer, are difficult to detect. In order to resolve such small motion, we need accurate displacement sensors. We currently have a fiber-optic interferometer that is able to measure a single step of the STM, which is roughly a couple nanometers depending on the voltage amplitude of the input signal. This is done by monitoring the interference pattern of a coherent light signal. With the additional capacitive sensor we create, we hope to detect motion with more accuracy when the STM head is extremely close to the sample, at nanometer scale.

With the data obtained, we hope to study the motion characteristics completely so that improvements of the STM motion control can be made in future experiments.

Objectives

Our main objective is to see if the capacitive displacement sensor method is sensitive enough to study the exact motion of the STM and the piezoelectric stacks. Since the capacitive sensor is self-made, the relationship between capacitance and displacement must be studied and understood. The goals for this experiment are, in order, design and optimize a capacitive displacement sensor, study and calibrate the sensor to obtain the capacitance-displacement relationship, obtain the precise motion of the STM when different voltage signals are applied and different pressure applied by the piezoelectric holders, and finally analyze the trend and behavior of the STM and the piezoelectric actuators.

CHAPTER II

METHODS

For the capacitive sensor, we started with the basic assumptions of simple parallel plate capacitors. We used a simulation program called FlexPDE[4] to optimize the design and attempted to make it a single ended detector that fits within the existing geometry of the STM. After a design was set, we machined it to test out the sensitivity and precision physically with an existing high precision capacitance bridge. After the sensor was constructed, we attached it onto the setup (shown in Figure 1) in order to calibrate it and ultimately measure the motion of the STM. We studied the characteristics of the piezoelectric motors by taking multiple data sets under varying circumstances that could affect the results such as the orientation of the STM, the applied voltage and clamping force on the piezoelectric stacks that hold the moving sapphire prism of the STM.

Displacement sensor fabrication

In order to construct a capacitive displacement sensor that fits within the existing apparatus inside the cryostat, planning and running simulations are required to maximize the effectiveness and sensitivity of the device. Due to the fact that the sapphire prism holding the STM only has a surface area of roughly 1cm^2, the sensor must be made at a comparable size. In this case, a single ended detection device is the design of choice. Since the idea was to utilize the high sensitivity of a capacitance device, it is only natural to refer to the inverse relationship between the capacitance and distance separation $C \propto A/d$ where A is the surface area of the parallel plate capacitor and d is the separation between the plates. However a single ended capacitive sensor in which two planar concentric capacitors couple to a conducting area on the STM may not follow this simple inverse relationship. The hope is that this configuration will follow a similar relationship of the parallel plate capacitors.

Simulation stage

The goal is to maximize the sensitivity (or maximize the change in capacitance versus the change in the gap separation distance) so that nanometer motions can be resolved. This is done by simulating, using the program FlexPDE, the relationship between capacitance and many other variables such has the spacing between the concentric capacitors, the areas of the capacitors, and the ratio of the two areas. After understanding how the detector is optimized, the next step is to design a device that maximizes the sensitivity and fits with the apparatus. With the dimension of the cryostat taken into account as well, the final simulation will determine the actual dimensions of the sensor created.

Testing stage

After the simulation phase and the construction of the actual device, the next step is testing the device. The single ended capacitive displacement sensor is mounted onto a stand facing a piezoelectric actuator that can expand or contract with varying lengths depending on the input AC voltage signal provided by a function generator. The stand that holds the piezo is also adjustable so that the distance between the sensor and the piezo can vary. Because this piezoelectric actuator is a commercial device, the factory manual provides detailed relations between the voltage amplitude of the input signal and displacement (1μm/100V). With this knowledge, one can study the relationship between displacement and capacitance of the device created. To do so, one simply takes many data points of distance versus capacitance. With sufficient data, one can fit the points with a function that can then predict the gap separation based on the capacitance.

Nanometer motion measurements

To truly measure the motion of a STM and the piezoelectric motors, the motion sensor must be able to pick up motion in the range of nanometers. To do this, the self-fabricated capacitive displacement sensor is mounted against an industrial piezoelectric. An AC voltage signal from a function generator is applied to the piezoelectric actuator to put a strain on the actuator itself. The picture below is the setup used to take this measurement.

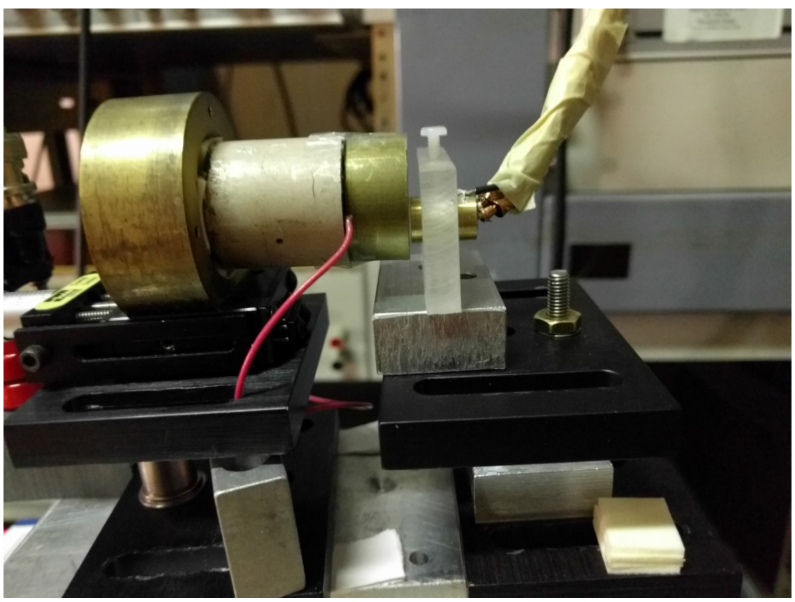

Figure 1: The setup for nanometer range measurements

In Figure 1, the capacitive displacement sensor is on the right, held by a nylon mount. The wires on the right connect the displacement sensor to the capacitance bridge. On the left, the industrial piezoelectric is connected to an amplifier that is then connected to a function generator. On the side of the piezoelectric is a conducting mirror that is used as the target of the motion sensor. When the function generator applies an AC voltage signal with variable voltage amplitude and frequency, the piezoelectric actuator either expands or contracts, moving the mirror, which changes the capacitance measured by the capacitance bridge.

STM piezoelectric measurements

To measure the actual STM motion, we replace the industrial piezoelectric actuator with the STM. The setup is the same as the one shown in Figure 1, but with the STM installed in place of the industrial piezoelectric. By applying signals with varying voltage amplitudes, one can study the motion of the piezoelectric actuators inside the STM.

CHAPTER III

RESULTS

From the hypothesis for the displacement sensor, the general parameters are similar to that of a parallel plate capacitor. The shape was ultimately chosen to be cylindrically symmetric and the areas of the two plates were set to be about equal. The areas are also maximized to increase sensitivity, while the inter capacitor spacing is minimized. At first sight, the measurements of the displacement sensor seem to agree with the inverse relationship between the capacitance and the displacement of a typical parallel plate capacitor. The inverse relationship is clear, meaning the closer the sensor is, the more sensitive it becomes. This can be shown by simply differentiating the capacitance with respect to gap separation. Given $C \propto A/d$, the sensitivity becomes $\Delta C / \Delta d \propto -A/d^2$. This shows that capacitance changes more rapidly with respect to a change in distance when the distance becomes smaller.

Figures 3, 4, and 5 indicate the relationship between distance and capacitance; these plots correspond to different radii settings during the optimizing stage from the simulation program FlexPDE. The different radii correspond to different surface areas, which can affect the sensitivity of the sensor as shown in the above relationship. Figure 2 roughly shows the sensor head of a single ended capacitive displacement sensor that was designed.

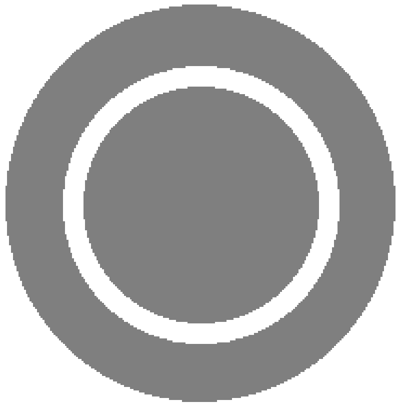

Figure 2: Schematic view of the face of the capacitive sensor. The grey portions are copper while the white is epoxy (not to scale)

The motivation for these different radii settings is mainly to compare the effects of the surface areas (A_1 for the inner cylinder and A_2 for the outer surrounding cylinder) on the sensitivity of the sensor. By optimizing, we want to maximize the sensitivity, again, meaning maximizing the change in capacitance relative to the change in displacement. These graphs are made under the assumption that there is a maximum radius which the outer cylinder cannot exceed. Under this restriction; we are trying to find a setting that maximizes C and $\Delta C/\Delta d$ which would increase the resolution.

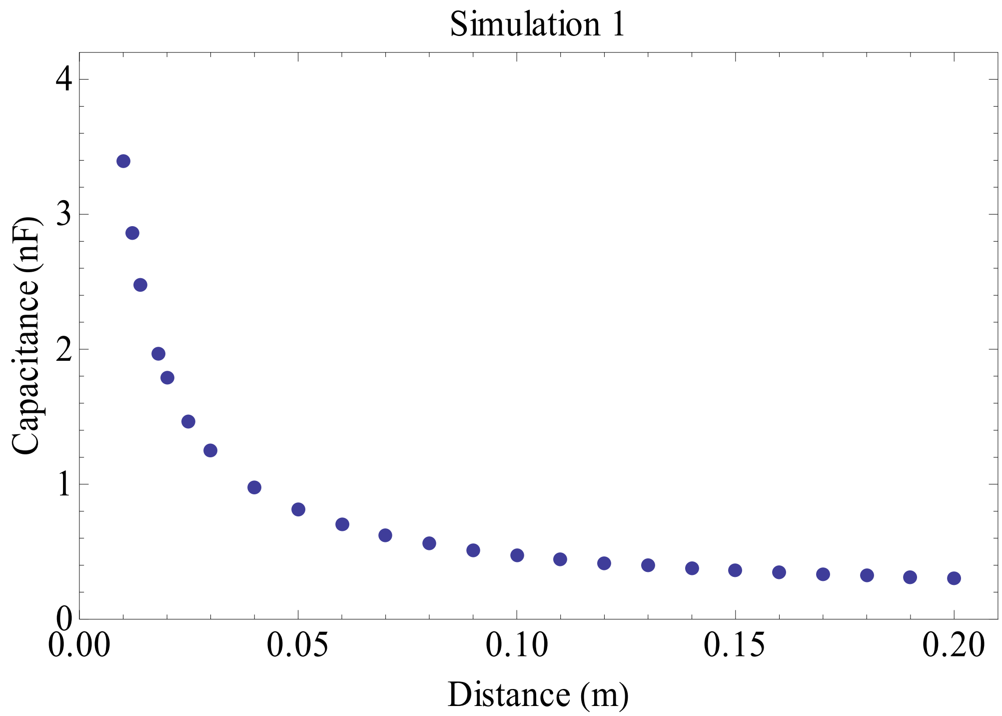

Figure 3: The areas of the cylinders are $A_1 = A_2 = \pi(2.25m)^2$.

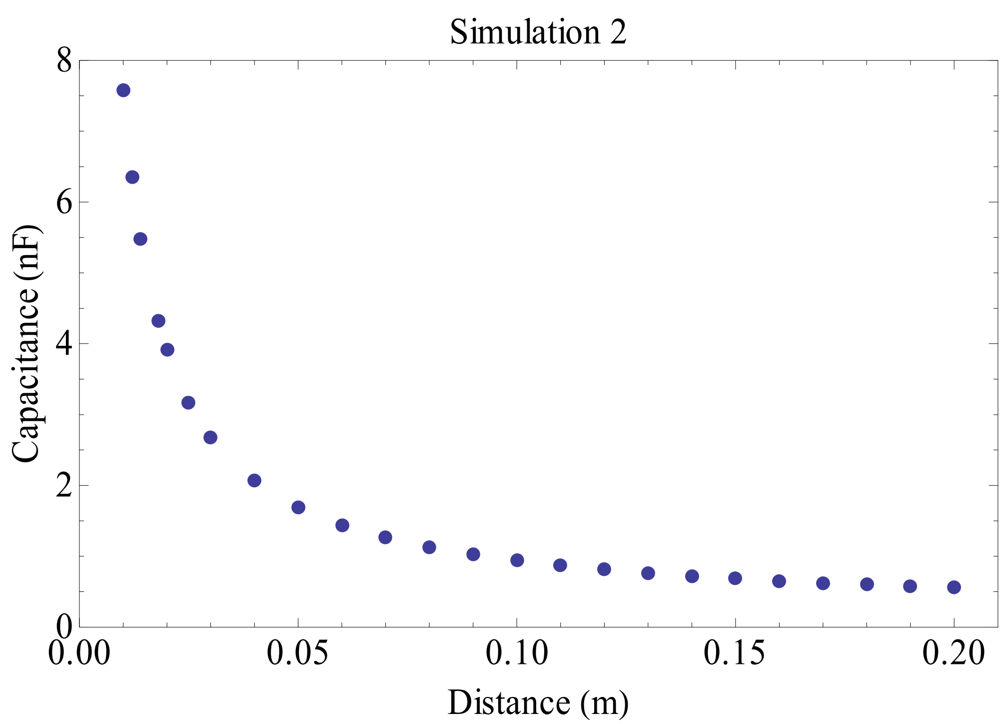

Figure 4: The areas of the cylinders are $A_1 = A_2 = \pi(2.28m)^2$. This is achieved by decreasing the spacing between the cylinders while keeping the overall area constant.

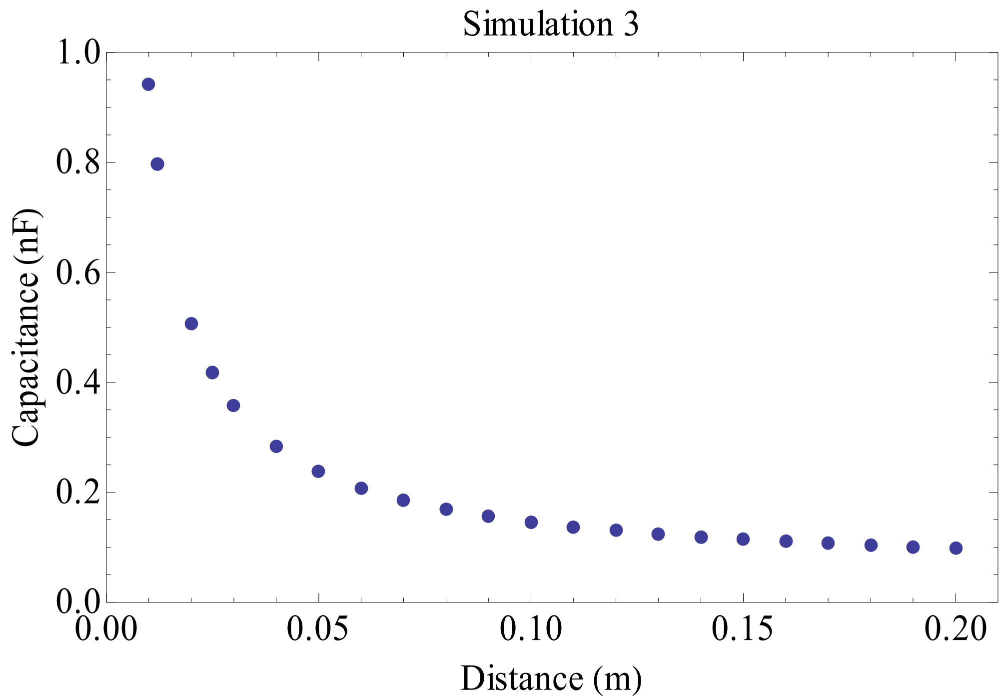

Figure 5: This is a trial in which the areas were chosen to be different, $A_1 = \pi(1.50m)^2$ **and** $A_2 = \pi\left((2.25m)^2 - (1.75m)^2\right)$**.**

The three plots shown have the exact same displacement range. Note that the vertical axes however are different for the three plots. The plot shown in Figure 4 is the one with the largest sensor area setting. The areas are set to be maximized under the circumstances that the sensor must fit with the existing apparatus, but at a blown up proportion. After learning that the biggest contribution to increasing the sensitivity is the size of the surface area, the logical plan is to fabricate the sensor such that the areas of the concentric cylinders are maximized. A couple more simulations were also made to test out the effects the ratio of the areas of the inner and outer cylinder have on the sensitivity, but the change in the sensitivity were mostly negligible until the ratios were relatively large or small compare to the ratio of one. Therefore, for the actual design, the decision was made to maximize both areas while keeping the areas the same. The material of choice for the sensor head was copper while the shielding around the capacitors was brass. The material used to separate the metal is insulating epoxy. The separation is crucial because a short between the two concentric cylindrical capacitors would cause the sensor to fail.

Actual sensor measurements

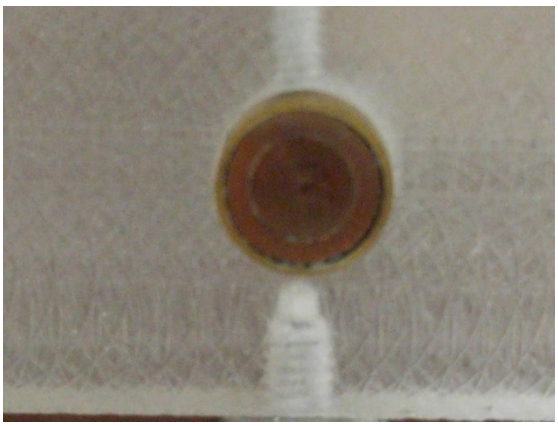

Figure 6: The sensor held by a holder for data measurements

The final sensor has a diameter of less than one centimeter (0.96 cm). To maximize the sensing area of the two concentric cylinders, the gap between them is filled with epoxy (the white line between the two copper pieces) which is only 250 microns in thickness. As mentioned in the methods section, the sensor is mounted facing an industrial piezoelectric actuator that gives known displacements so that the changes in the capacitance can be calibrated. The capacitance of the sensor head is measured by a very precise capacitance bridge and the output is recorded. Figures 7 and 8 (next page) show the relationship between the capacitance (y axis, pF) and the distance (x-axis, μm) from the target over 8 sets of data. The four different colors in each plot indicate four different sets of data points. One can see that as the distance decreases, the sensitivity increases dramatically but the deviations start to be more apparent.

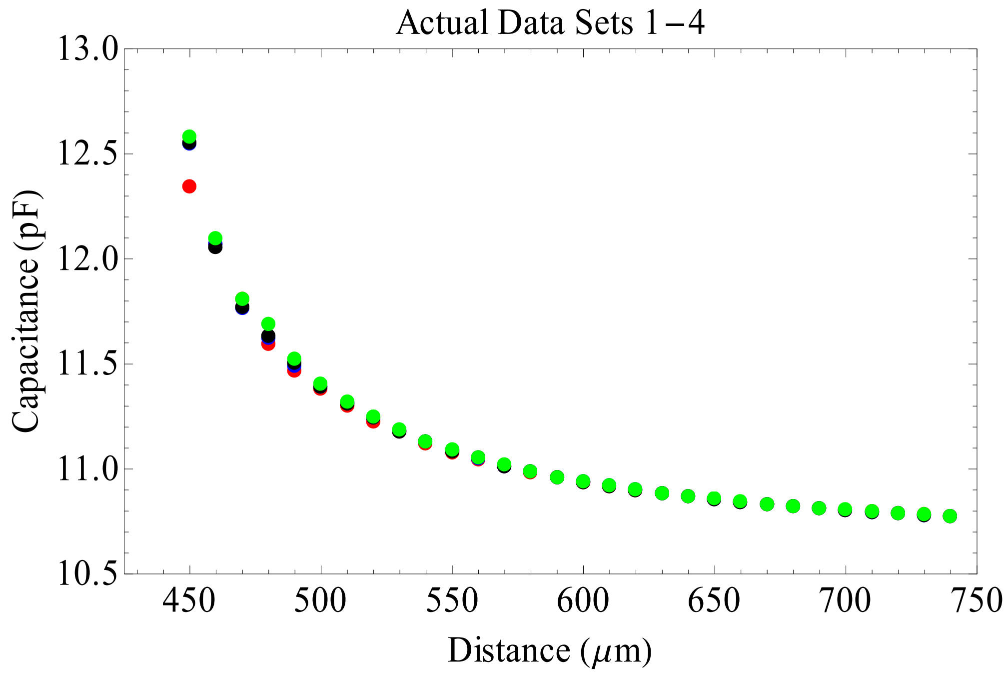

Figure 7: Four data sets taken at the same range of displacement

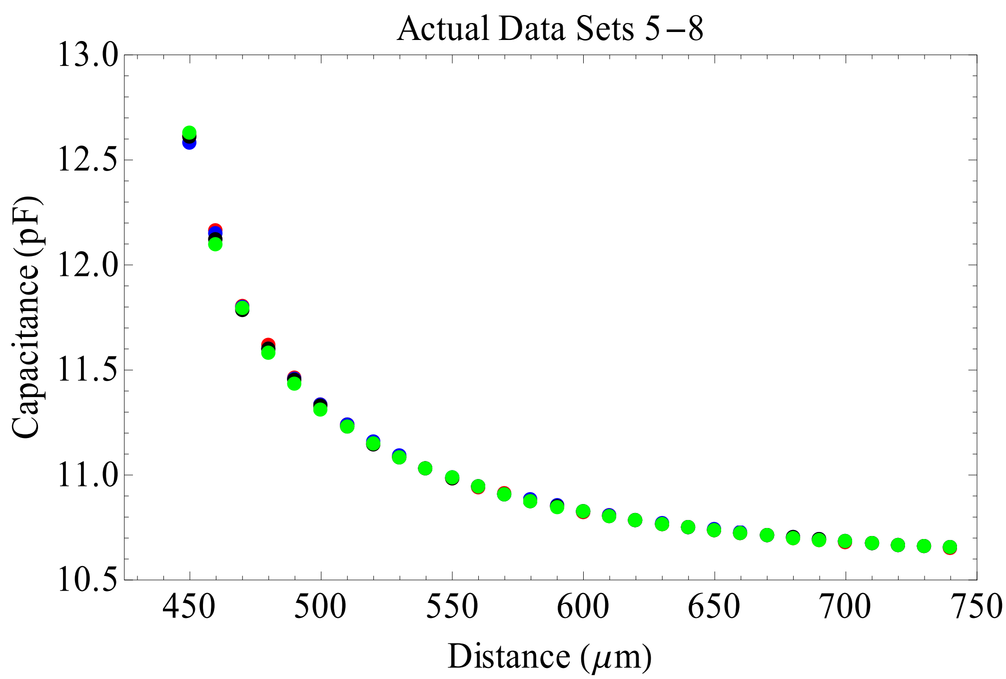

Figure 8: The data points of these 4 sets were taken after a realignment of the sensor and the piezoelectric actuator. The data points are more consistent compared to the first four sets.

It is obvious that the distance and capacitance are inversely related, but it is not absolutely clear that the relationship is strictly a $1/d$ dependence as in a parallel plate capacitor. To test this, the data is inverted so that the capacitance is plotted as a function of $1/d$, where d is the distance. Figures 9 and 10 show the same eight sets of data shown in Figures 7 and 8.

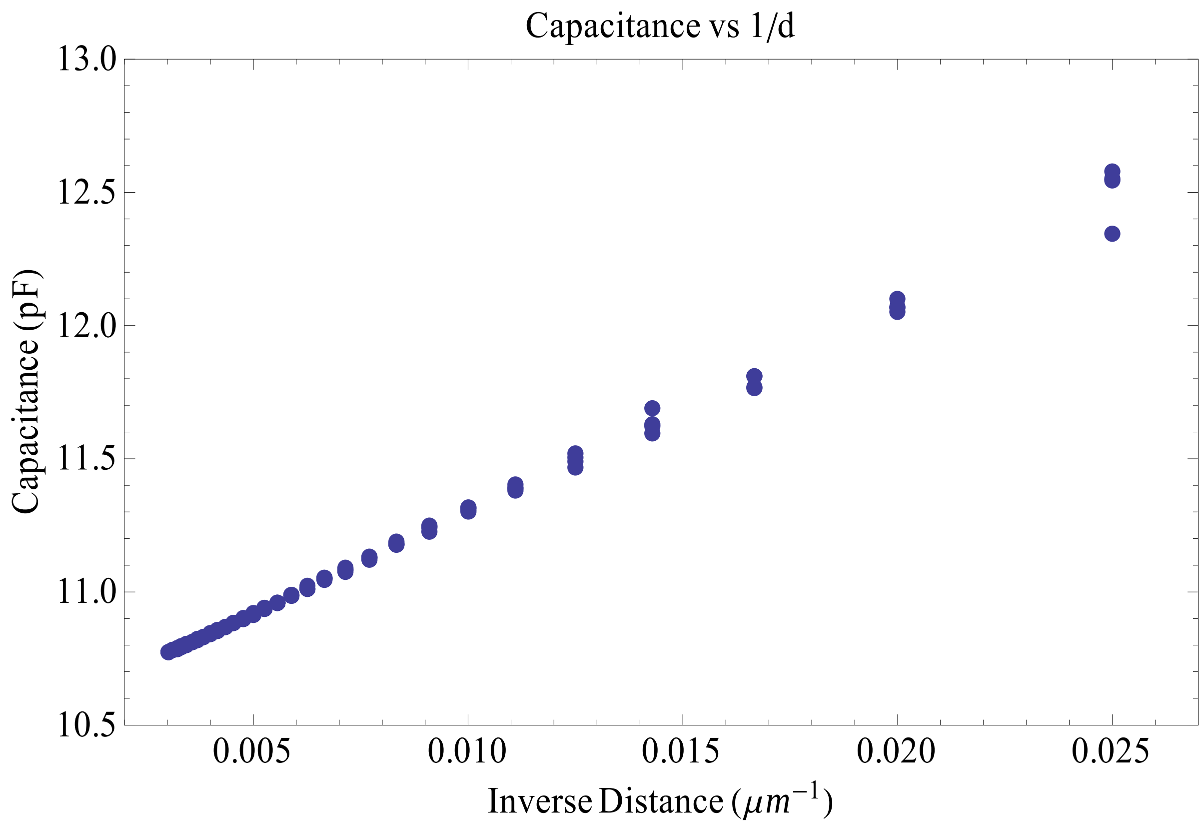

Figure 9: This graph shows capacitance as a function of $1/d$ for data sets 1-4

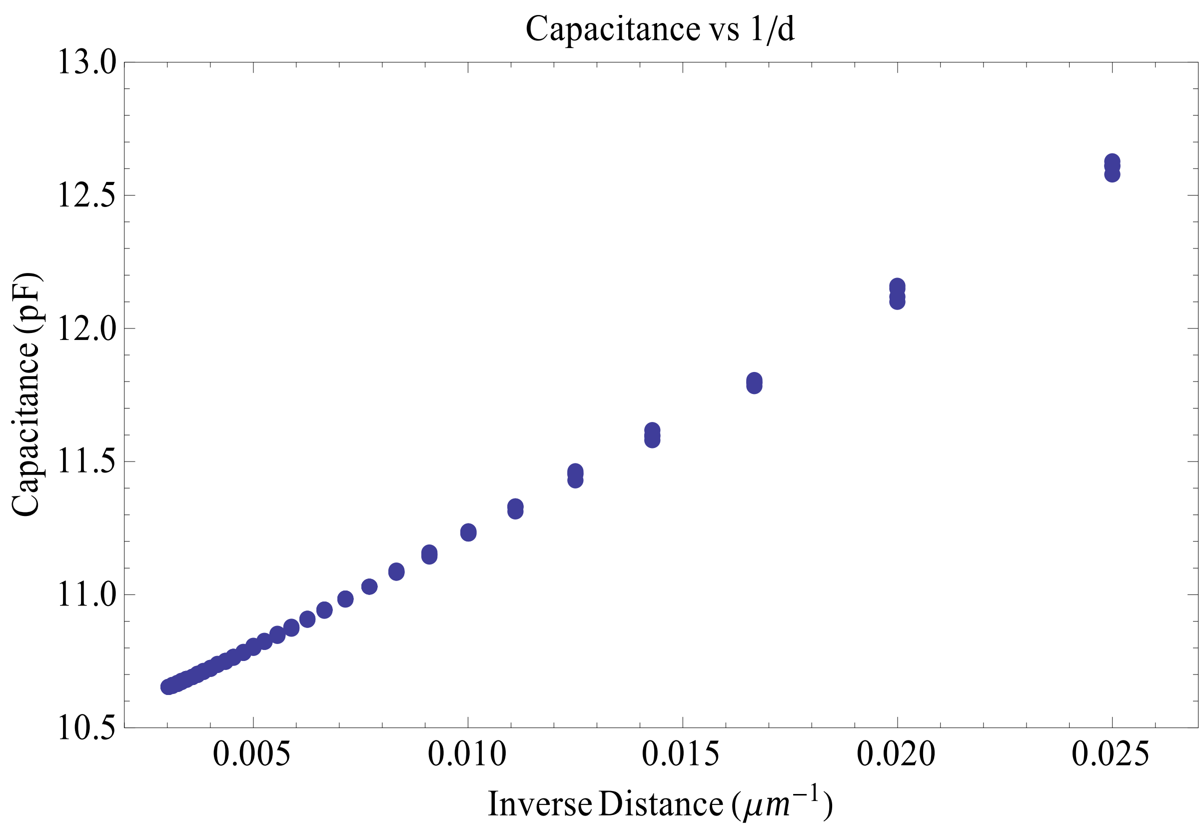

Figure 10: This graph shows capacitance as a function of $1/d$ for data sets 5-8

As one can see the dependence on $1/d$ is very close to linear, suggesting that the capacitance does follow the $1/d$ dependence. To make sure there are no hidden dependencies of higher order, one can plot the residuals and hope for a random scatter for both of the C versus d plots.

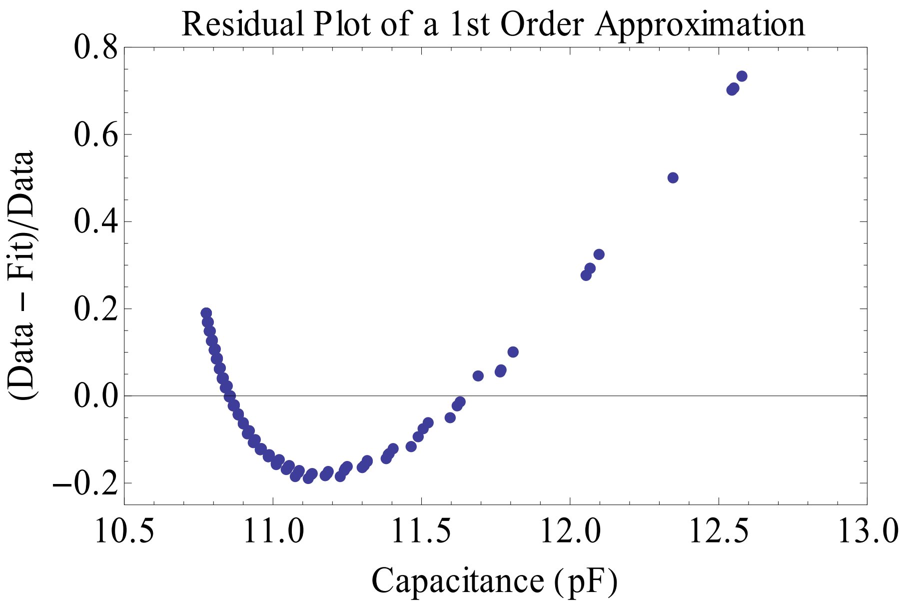

Figure 11: This graph shows the residuals of a $1/d$ fit to the capacitance data

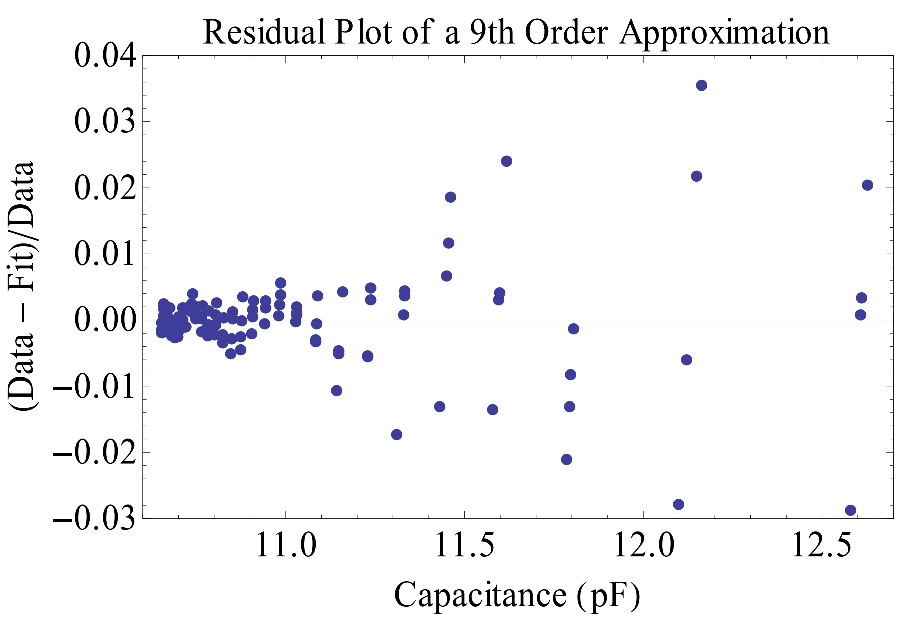

Figure 12: The 9th order $\left(C = \sum_{n=1}^{9} a_n d^{-n}\right)$ approximation has a much more random residual distribution

The residuals do appear to be in a more random pattern therefore suggesting higher order dependence. The final fit equation includes up to the negative ninth power and will be used to extrapolate displacements from the piezoelectric motion used later.

Nanometer motion measurements

In this stage, we attempted to measure nanometer range motion with the displacement sensor After setting up the system, a 50Vp-p square wave is applied to the piezoelectric actuators; this corresponds to a 0.5μm increment movement of the industrial piezoelectric. The fixed distance between the piezoelectric mirror and the motion sensor is set at 360μm for 50V and 10V, 330μm for 5V. Below are some figures of the capacitance output at various signal amplitudes (different voltages) with the signal type chosen to be square waves.

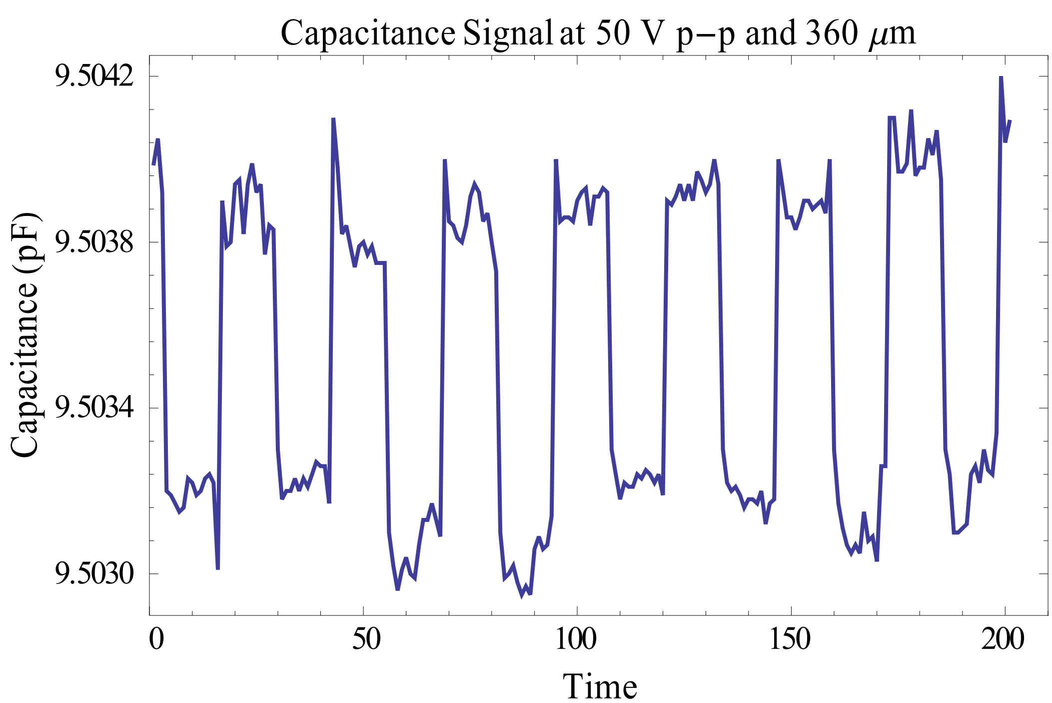

Figure 13: The data is taken with a 50V p-p square wave input signal and a 360 μm separation

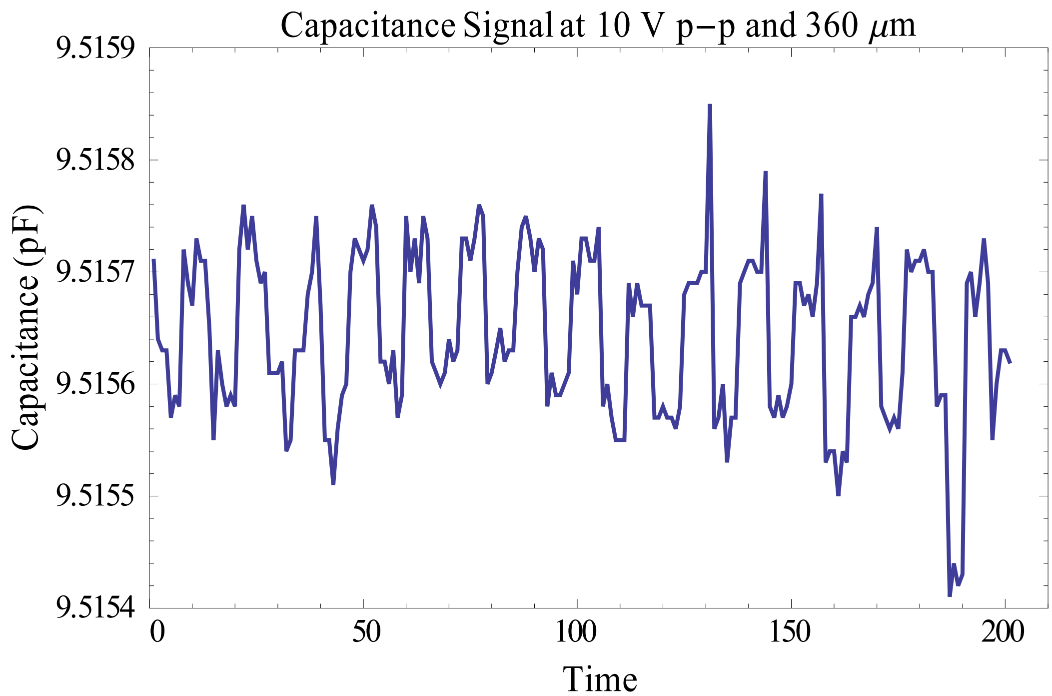

Figure 14: The data is taken with a 10V p-p square wave input signal and a 360 μm separation

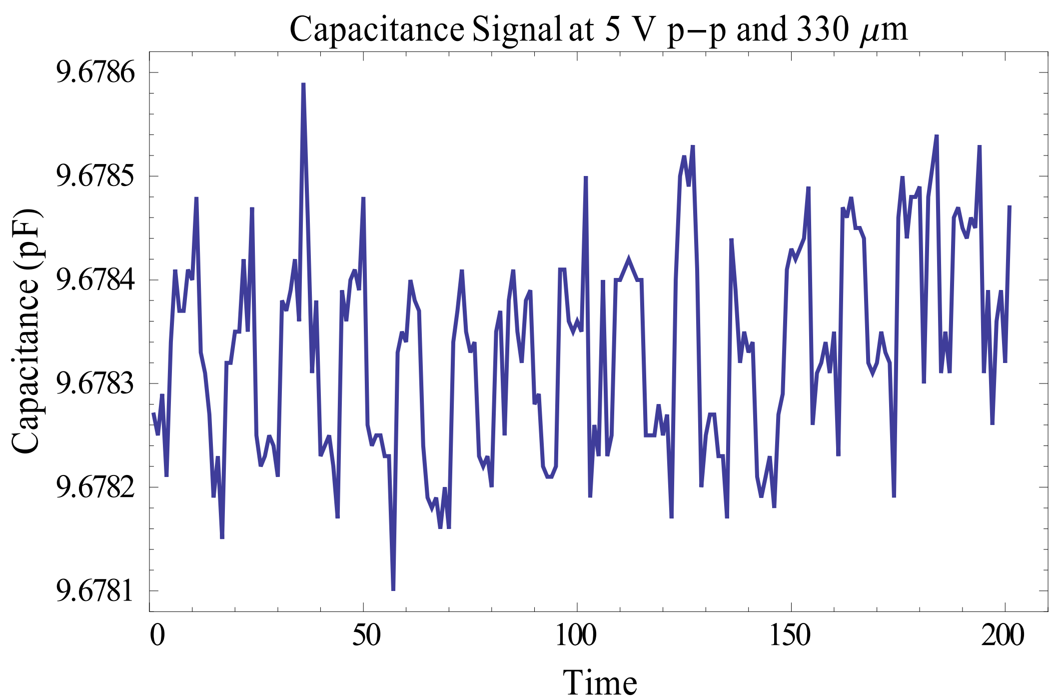

Figure 15: The data is taken with a 5V p-p square wave input signal and a 330 μm separation

From the three different amplitude settings in the figures, one can clearly tell that when the amplitude is smaller, the noise becomes much more significant. In the 50V setting (this corresponds to a 0.5μm movement of the piezoelectric) the behavior of the piezo is captured extremely well, with minor kinks that may simply correspond to the odd motion of the piezo. In the 10V (100nm) setting, the relative noise is much more significant and even more so in the 5V (50nm) setting. Although noise is present, the general shape of the motion is still observable. When the applied amplitude is reduced to 1V (10nm), the output is dominated by noise and no real motion is observed. Since the signal is much stronger when the distance between target and sensor is closer, the next step is to retake some measurements at a closer distance between the mirror and the motion sensor.

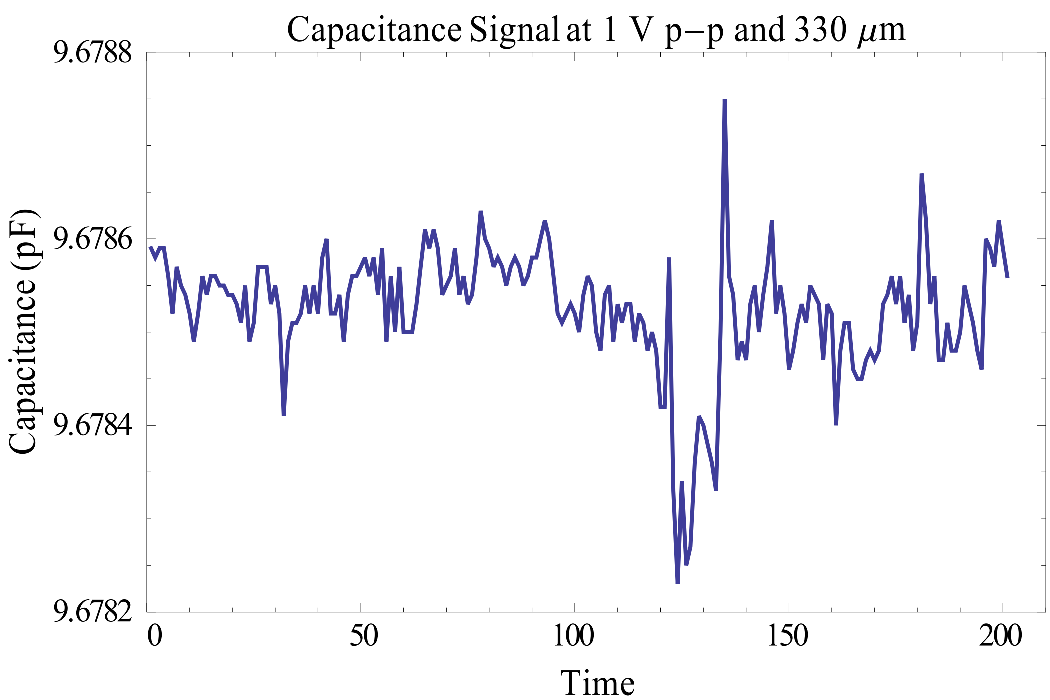

Figure 16: The data is taken with a 1V p-p square wave input signal and a 330 μm separation

Problems with the displacement sensor at nanometer scale

While taking data that produced Figure 16, it was discovered that the motion sensor did not have a smooth enough sensing surface for higher resolution. Ideally one would decrease the distance between the sensing surface and the target and retake data at the same amplitude (1V) to compare results. In this case, the decision was to test out similar effects by increasing the voltage amplitude and increasing the separation distance to a point where a 5V signal is noisy. From there on, one can reproduce a better result by decreasing the separation distance. The two graphs below (Figures 17 and 18) show how decreasing the separation (moving the sensing area closer to the target) increases the resolution of the capacitance signal output, which produces a better understanding of the piezoelectric motion.

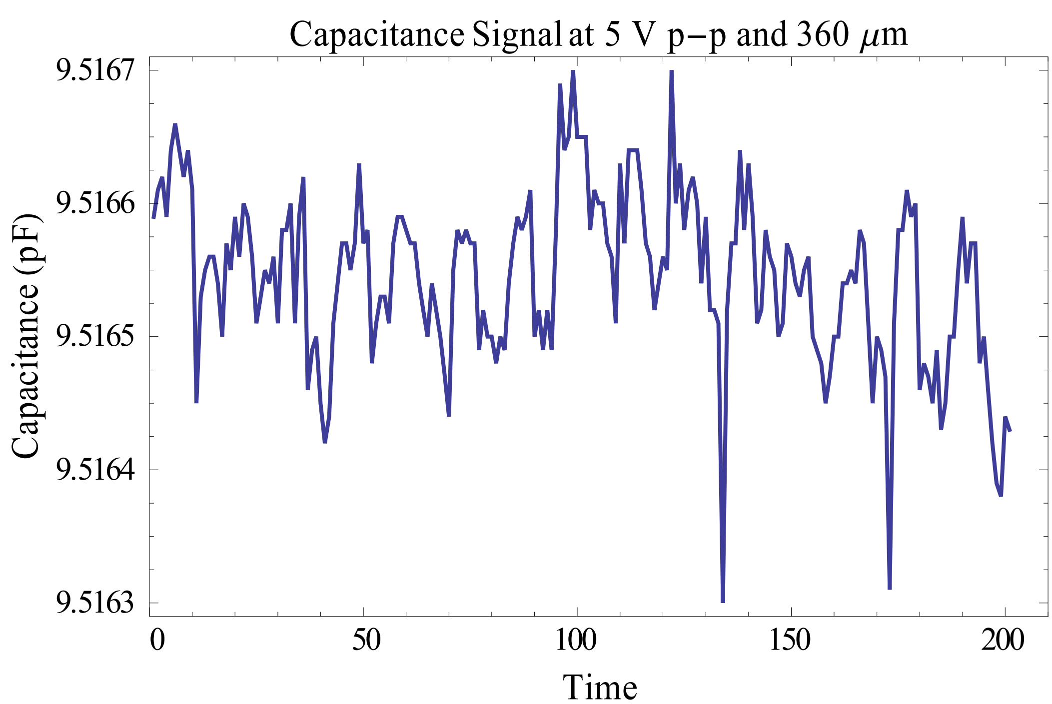

Figure 17: The data is taken with a 5V p-p square wave input signal and a 360μm separation

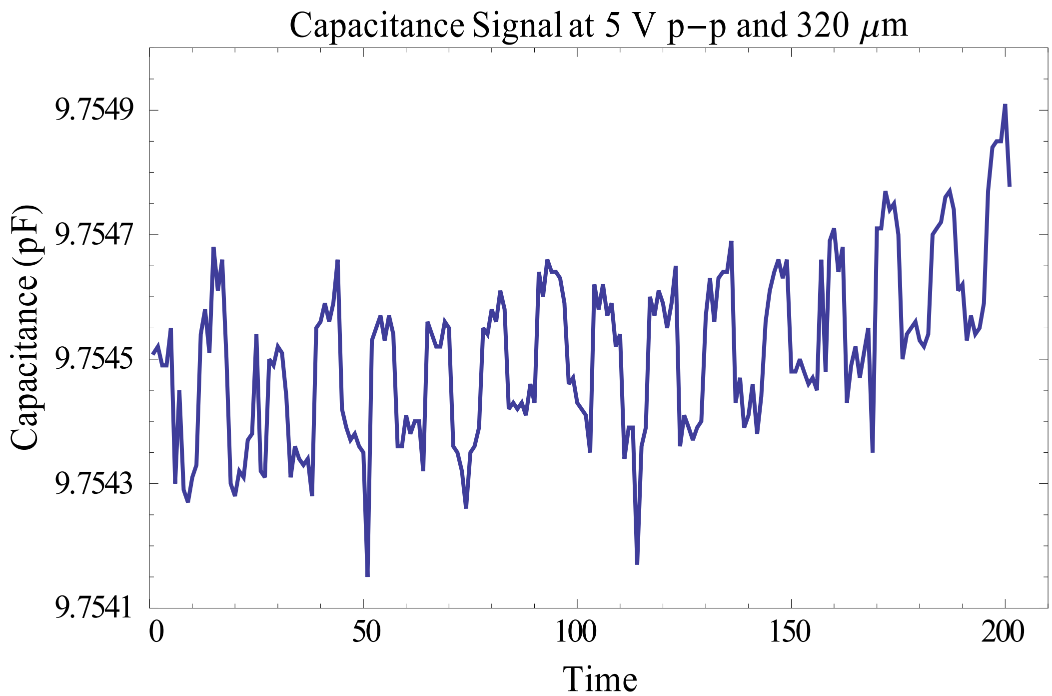

Figure 18: The data is taken with a 5V p-p square wave input signal and a 320μm separation, the resolution in this case is much higher

Measurement for the STM

After finding out the limitations of the capacitive displacement sensor, some data of the STM motion was taken with a similar set up as the previous stage.

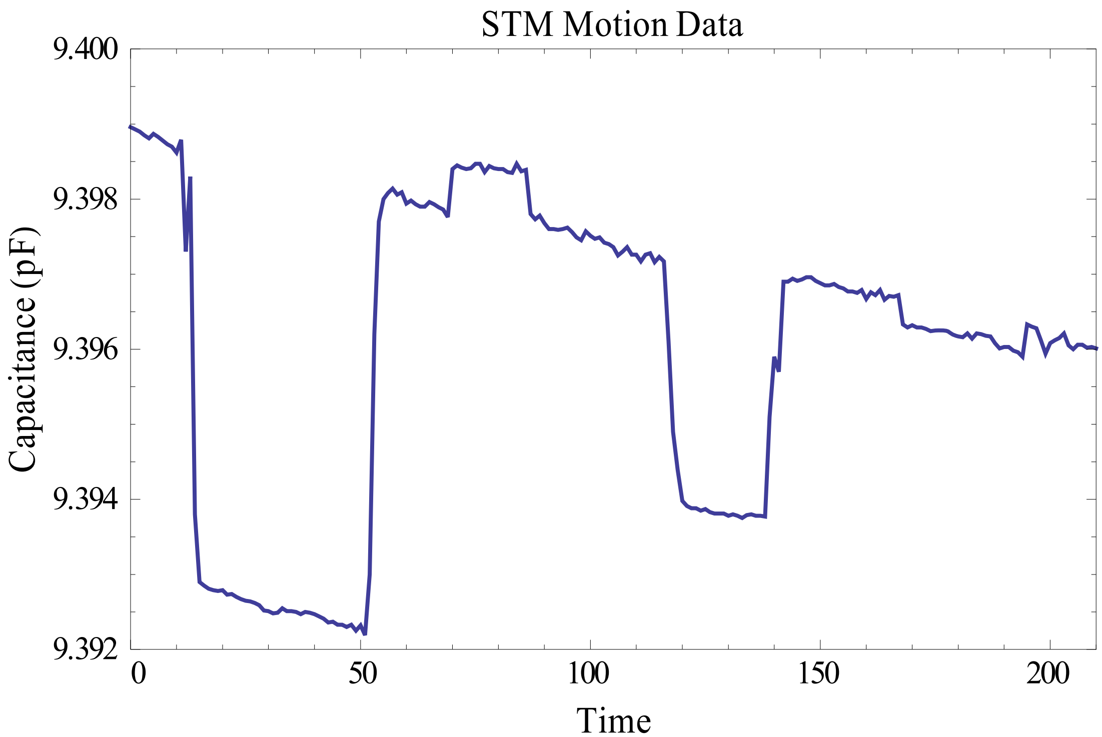

Figure 18: This shows the STM motion with various input signals as described in the text

In this set up, the STM was placed in such a way that forward motion results in the STM moving farther away from the target and causing the capacitance to decrease. The signals are sent to the STM to make it move in the following way: 100 (150V) steps forward, 100 (150V) steps backward, 10 (150V) steps backward, 10 (150V) steps forward, 100 (90V) steps forward, 100 (90V) steps backward, 10 (90V) steps forward, and 10 (90V) steps backwards. From Figure 18, one can see that the first big drop in capacitance corresponds to the forward movement. Another 100 steps at 150V is applied and this time in a backwards fashion, causing the capacitance to increase by the same amount. In this graph however, due to the high sensitivity of the capacitance bridge, it may have picked up some noise, causing a slow downward drift; otherwise the change in capacitance is almost identical for the forward and backward motion. This drift in capacitance occurs randomly in the capacitance bridge. While sometimes the capacitance as measured by the bridge stays relatively constant, sometimes the values start drifting either upwards or downwards. The cause of this is unclear and from testing we have excluded the function generator and the signal amplifier as potential issues. The drift could be due to thermal drift, but previous experiments that provided simple thermal shielding also did not improve the situation by much. This may also be caused by the capacitance bridge itself, but it is not certain at this point.

CHAPTER IV

CONCLUSION

Using the basic physical laws and some computer simulation, we were able to design and fabricate a capacitive displacement sensor. By testing the sensor, we were able to deduce that the characteristics still resemble that of a parallel plate capacitor even with the concentric cylindrical shape we have in our design. Putting the capacitance sensor to test, we were able to get results from the motion of the STM. Although the resolution of this particular capacitive displacement sensor may not be as high as we expected, this method shows promise for future uses.

The drift and noise

It is noted that due to the high precision and sensitivity of the capacitance bridge, small fluctuations may be picked up, causing the output to display noise in the signal. These fluctuations mainly consist of vibrations and temperature change. Bad wiring of the system can also cause noise but this can be prevented rather easily. Vibrations could cause the separation between the sensing area and the target to alter slightly, which in the nanometer regime can be very significant. Vibrations can also cause the wires to shift in position, causing a change in the capacitance reading. This effect however, could be greatly reduced by using coaxial cables. Thermal effects may be the most significant of them all. While taking some of the data for this experiment, it is noted that whenever the setup is near any heat source, the data changes quite dramatically. The effect is minimized by taking data with a computer in a separate room.

Method applicability

In this particular experiment, we were unable to build a capacitive displacement sensor with enough resolution to view a single step of the STM even with a 150V signal. The main problem was that the sensing area of the probe was not flat and smooth. Certain edges of the sensing area would make contact with the target causing major changes in the capacitance reading. Although these protruding edges are not the capacitor itself (it could be one of the cylinders, but not both, otherwise there would be a short), they are most likely part of the grounding guard around the capacitor. This effect limits how close the sensor can be brought towards the target. Another factor is how precisely the target is placed facing the sensor. Ideally they should be placed with the surfaces completely parallel with each other so a part of the surface does not make contact before the other. In this experiment, there was not a surefire way of making that the case. The best solution was eyeballing with powerful magnifying lenses when the two surfaces are brought close to each other.

Even with these imperfections, the capacitive displacement sensor is still able to pick up nanometer motion. At the given settings, the sensor is able to detect 50nm motion as far as 320μm away from the target with great resolution with the added benefit that it could also tell the direction of motion, which the interferometer could not. Applied in the coarse approach scenario, this sensor could work when the STM is within around 300μm of the target. To detect motions in the range of Angstroms, the capacitance would need to be machine more finely. Due to the fear of crashing the tip of the STM to the sample, one would have to fix the problems listed above for the method of motion detection to work. If the displacement sensor is allowed to function while being placed much closer to the target, the resolution could theoretically be increased making motion detection at the Angstrom level possible. Due to the nature of capacitors and the inverse relationship between separation and capacitance, this method should be the ideal one for motion detection. When put in a cryostat, the thermal and vibrational noise is also minimized, causing the readings to be much more accurate. As long as one overcomes the barrier of machining this device, it could be the most effective method of motion detection for STM's.

REFERENCES

[1]-Oura, K., M. Katayama, V.G. Lifshitz, A.A. Saranin, and A.V. Zotov. *Surface Science an Introduction*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003.

[2]- Chen, C. Julian. *Introduction to Scanning Tunneling Microscopy*. New York: Oxford UP, 1993.

[3]-Hii, King-Fu, R. Ryan Vallance, and M. Pinar Mengüç. "Design, Operation, and Motion Characteristics of a Precise Piezoelectric Linear Motor." *Precision Engineering* (2009): 231-41.

[4]-"FlexPDE Finite Element Model Builder for Partial Differential Equations." *FlexPDE Finite Element Model Builder for Partial Differential Equations*. Web. 10 Apr. 2016.